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Predictive Geometry-Matched UV-LED Delivery for Complex Three-Dimensional Surfaces

Technical Architecture, State of the Art, and Phase I Research Framework

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Abstract

Complex three-dimensional surfaces challenge UV-LED curing because source-to-surface distance, incidence angle, optical access, source overlap, and shadowing vary across the workpiece. Existing approaches include fixed arrays, spot sources, specialized optics, light guides, source or part motion, and application-specific illumination geometries.

WPR is investigating a reconfigurable geometry-matched source architecture in which source positions and orientations are derived from known target geometry. A bounded empirical field model, anchored to individual-source characterization, would predict target-surface irradiance before confirmatory radiometry. The research logic is Prediction → Improvement → Reproducibility: predictive adequacy must precede an uncertainty-resolved comparison against an equivalent rigid arrangement, and any advantage must survive independent physical reconstruction.

This report synthesizes the technical rationale, relevant prior art, configuration method, metrology requirements, and proposed Phase I experimental framework. It presents a research foundation and testable hypotheses; it reports no new experimental performance results.

Research status and scope

> This technical report documents WPR's pre-Phase-I research architecture, state-of-the-art analysis, engineering hypotheses, and proposed experimental framework. It does not report completed Phase I experimental validation or claim demonstrated commercial performance.

The completed pre-Phase-I work comprises literature synthesis, architecture definition, engineering hypotheses, and experimental and decision-framework development. Source characterization, geometry-to-field validation, repeated-reconstruction comparisons, cure-response testing, and representative interface-risk experiments remain proposed. This is a WPR technical report, not a peer-reviewed article, an NSF award result, a patent filing, or qualification of a commercial product.

Industrial problem

Delivered irradiance is a spatial quantity on the receiving surface, not a synonym for source output. Across a curved or recessed substrate, local surface normals, working distance, angular source response, occlusion, and overlapping illumination jointly determine the incident field. Radiant exposure additionally depends on exposure history. Material response depends on spectral compatibility, photoinitiator kinetics, attenuation, and thermal conditions; equal nominal dose alone does not establish equivalent cure [1].

Citation and permanent publication record

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STATE OF THE ART AND RESEARCH ARCHITECTURE

State of the art and technical gap

LED-array spacing and layout are established variables for near-field uniformity [2]. More recent work validates spatial irradiance models and optimizes emitter placement subject to practical constraints [3]. UVA surface-scanning radiometry demonstrates the importance of working distance and spatial mapping [4]. Geometry-specific pipe-curing sources have been modeled and evaluated radiometrically, and UV-LED-curable pipeline coatings have been demonstrated [5, 6]. Modular, individually controlled, water-cooled LED architectures also have precedent [7].

These precedents narrow WPR's research question. UV LEDs, modularity, water cooling, non-planar curing, and geometry-specific illumination are not individually claimed as novel. The unresolved question addressed here is whether a common reconfigurable architecture and deterministic configuration method can retain predictable, reproducible delivery across different target geometries. This is a research gap motivating an experiment, not a claim of exhaustive prior-art clearance.

Geometry-matched research architecture

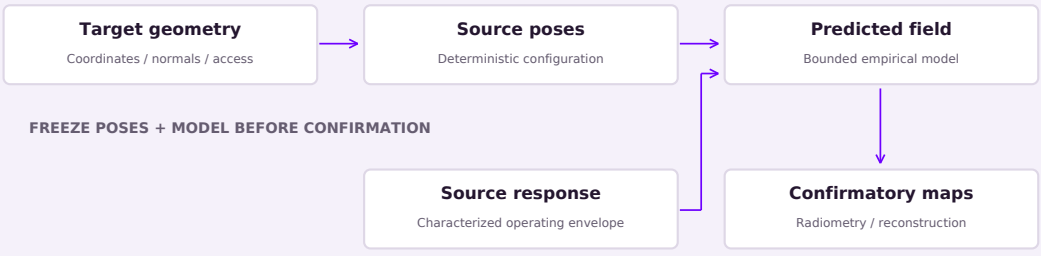
The architecture separates three objects: the registered target geometry, the source configuration, and the resulting target-surface field. Target locations are described in a common coordinate frame with local normals and accessibility information. Source pose means both source position and optical-axis orientation. A reproducible transformation from geometry to pose is essential: subjective repositioning after inspecting a confirmatory map would confound the hypothesis.

The proposed deterministic method assigns predefined target regions to characterized sources, uses region centroids and representative local normals to initialize source poses, and permits only bounded model-based refinement within a previously characterized operating envelope. Clearance, fixture constraints, and radiometric access bound admissible configurations. The selected poses and model parameters are frozen before confirmatory mapping. Detailed hardware embodiments, interface designs, and implementation parameters are outside this public report.

PRIMARY RESEARCH QUESTION

Can calibrated, reconfigurable identical UV-LED sources be configured from known three-dimensional target geometry so that the resulting target-surface irradiance and radiant-exposure field can be predicted within a defined error bound, while producing a repeatable improvement in spatial uniformity and low-dose coverage relative to a rigid source arrangement?

FIGURE 1 / PROPOSED RESEARCH ARCHITECTURE



Conceptual schematic only. Source characterization precedes the freeze; confirmatory maps test the frozen prediction. No performance data are depicted.

FIELD PREDICTION AND METROLOGY

Predictive field framework

For a target point x, predicted irradiance is represented conceptually as the sum of characterized source contributions: $\hat{E}(x) = \Sigma_i V_i(x) K_i(x; p_i)$. Here p_i denotes source pose; K_i is a bounded empirical response incorporating source-to-target distance, source orientation, and receiving-surface orientation; and V_i represents direct line-of-sight visibility. The equation defines the model structure, not a validated predictive result. For time-dependent exposure, radiant exposure is $H(x) = \int E(x,t)\, dt$. Irradiance E is expressed in W/cm^2 and radiant exposure H in J/cm^2.

The empirical response must be characterized with the relevant detector geometry and source spectrum. A universal inverse-square or Lambertian approximation is insufficiently justified for extended, optically conditioned sources at short working distance. Interpolation is restricted to the characterized envelope; uncharacterized extrapolation cannot support a primary conclusion. Direct-field visibility does not establish that interreflections, scattering, or other indirect contributions are negligible: such omissions are potential model discrepancy.

No machine-learning requirement is imposed. Confirmatory maps must not be used for post-hoc tuning of the corresponding source pose or prediction. Any model revision informed by screening data requires a new freeze before subsequent confirmatory evaluation. Prediction error must be interpreted together with measurement uncertainty and reported residual structure [2-4].

Measurement and metrology framework

The planned sequence begins with individual-source characterization: head-to-head output, working-distance and angular response, temporal stability, and repeatability. Target-surface mapping must preserve coordinate registration, detector receiving-plane orientation, spatial sampling definitions, and source settings. UV radiometry is sensitive to spectral mismatch, out-of-band response, nonlinearity, and geometric or spatial response [8]. Broadband-detector calibration is source-spectrum dependent; 365-nm metrology findings cannot simply be treated as a calibration for a 405-nm experiment [9].

A difficult-access measurement pathway must be transfer-qualified against the primary radiometric pathway in common accessible fields before contributing primary quantitative evidence. Its residual transfer error enters the combined uncertainty budget. Calibration, source drift, detector angular response, positioning, registration, and setup reconstruction must be considered. If measurement uncertainty prevents resolution of the hypothesized effect, the result is inconclusive and the measurement pathway must be corrected before an architecture conclusion is accepted.

Proposed Phase I comparisons

The planned optical apparatus uses four independently controlled, nominally identical approximately 405-nm LED heads as a research proxy. At approximately 405 nm the emission is near the UV-visible boundary and is commonly described as violet; the UV-LED terminology here follows the curing-system application. The commercial source apparatus is not a completed FlexBeam product. Its air-cooled operation cannot validate a future liquid-cooled FlexBeam network.

The same characterized heads would illuminate flat, convex, concave, and recessed targets in rigid and geometry-matched arrangements. The rigid condition preserves relative source positions and nominally parallel axes; the matched condition derives poses from geometry. Comparisons at matched operating settings would be supplemented by normalized field-distribution analysis to distinguish improved spatial delivery from a simple increase in mean irradiance.

Planned endpoints include prediction error, spatial coefficient of variation (standard deviation divided by mean), minimum-to-mean irradiance, hotspot-to-mean irradiance, a predefined low-dose-region fraction, and radiant exposure. Low-dose thresholds must be defined before confirmation and interpreted within the chosen material and exposure conditions. Independent setup-reset reconstructions, rather than individual points within a map, are the experimental replicates. Bounded cure-response work would examine process relevance for one representative coating; separate representative interface-risk testing would screen implementation barriers without constituting lifetime or product qualification.

DECISION LOGIC, LIMITATIONS, AND REFERENCES

Technical risks and decision logic

Key risks include pose or registration error, detector mismatch, unqualified difficult-access measurements, drift, occlusion or indirect-field model discrepancy, and uncertainty larger than the geometry effect. Increased mean irradiance alone does not establish improved spatial field control.

GO	Prediction, distributional improvement, and reconstruction repeatability meet predefined criteria within the tested envelope, with tractable implementation risks.
NARROW GO	Evidence supports a restricted geometry or application class; conclusions remain confined to that envelope.
REDESIGN	A correctable modeling, metrology, positioning, or interface limitation prevents acceptance under the current configuration.
NO-GO	The architecture fails to establish a meaningful, reproducible advantage, or implementation burdens negate the optical benefit.

Manufacturing relevance, limitations, and conclusion

If validated, geometry-aware delivery could inform coatings and adhesive application engineering. Its manufacturing value must be compared with established optics, motion, and fixturing. No measured cost, energy, cycle-time, waste, or carbon benefits are claimed.

WPR reports no experimentally validated prediction error, uniformity gain, cure improvement, operating envelope, reconstruction tolerance, cooling performance, or service life. Generalization beyond tested geometries, sources, and chemistry remains unvalidated. Optical feasibility alone would not establish commercial competitiveness, safety qualification, patentability, or freedom to operate.

This pre-Phase-I work defines a falsifiable architecture for subsequent experimental validation. Prediction, uncertainty-resolved improvement, and reconstruction reproducibility must all be tested; narrowed or negative findings remain legitimate outcomes.

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